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^{48}Ti(n,xnypz$\alpha\gamma$) reactions for neutron energies up to 250 MeV

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Abstract. Cross section measurements were made of prompt γ-ray production as a function of incident neutron energy on a ^{48}Ti sample. Partial γ-ray cross sections for transitions in $^{45-48}$Ti, $^{44-48}$Sc, $^{42-45}$Ca, $^{41-44}$K, and $^{41-42}$Ar have been determined. Energetic neutrons were delivered by the Los Alamos National Laboratory spallation neutron source located at the LANSCE/WNR facility. The prompt-reaction γ rays were detected with the large-scale Compton-suppressed germanium array for neutron induced excitations (GEANIE). Neutron energies were determined by the time-of-flight technique. The γ-ray excitation functions were converted to partial γ-ray cross sections taking into account the dead-time correction, target thickness, detector efficiency and neutron flux (monitored with an in-line fission chamber). The data will be presented for neutron energies between 1 to 250 MeV. These results are compared with model calculations which include compound nuclear and pre-equilibrium emission.

INTRODUCTION

The capability to measure neutron cross sections over a wide range of neutron energies up to several hundred MeV provides a unique opportunity to test reaction model calculation codes. Cross section measurements using fast neutrons have been reported typically over a narrow energy range or at a single energy (usually 14 MeV). Therefore, there is a lack of data on neutron-induced reaction for higher energies. As the incident neutron energy increases above ≈10 MeV, a region is entered where preequilibrium reaction becomes increasing important, which has not been well explored with neutron-induced reactions. The main motivation for performing the present experiment was to provide an experimental data base for comparison with the results of nuclear model calculations and to test calculations based on Hauser-Feshbach formalism incorporating preequilibrium models for particle emission over a wide incident-particle energy range.

Titanium was chosen as sample material to complement existing high-energy neutron cross section data on targets ranging from ^{27}Al to ^{209}Bi. In addition, there exists a good data base for proton-induced reactions on Ti [1, 2]. The results of this work complement the existing data base and they may be used for detailed comparisons between the results of proton and neutron-induced reactions.

EXPERIMENTAL SETUP

The experimental data were obtained at the Los Alamos Neutron Science Center (LANSCE) Weapons Neutron Research (WNR) facility. A natural W target was bombarded by the 800 MeV pulsed-proton beam from the LANSCE linear accelerator. The proton beam consisted of micropulses 1.8 μs apart bunched into macropulses 625 μs in length. As a result of the spallation reactions, neutrons with energies from a few keV to nearly 800 MeV are produced. The GEANIE (GErmanium Array for Neutron Induced Excitations) spectrometer [3] is located about 20 m from the neutron source on the 60 degree right flight path. One main goal of the GEANIE project was to measure γ-ray production cross sections from neutron-induced reactions, and thus the array has been optimized for this purpose. GEANIE consists of 11 planar and 15 coaxial detectors. All of the planars and 9 of the coaxial detectors were equipped with BGO suppression shields. The planar detectors were used to measure γ-rays with energies less than 1 MeV and coaxial detectors up to 4 MeV.

The incident neutron energy was determined by the standard time-of flight (TOF) technique. The data were collected for about 6 days with a 3.3 gram, 2.4 cm diameter, TiO_2 target enriched to 99.81% in ^{48}Ti. A total of about 4.6x10^8 single- and higher-fold γ-ray events were recorded. The neutron flux is monitored by in-beam ^{235,238}U fission chambers, located 2 m upstream from the array [4].

DATA ANALYSIS

During data playback, events were separated into in-beam and out-of-beam matrices, and 2D matrices for E_γ vs. TOF and $\gamma\gamma$ coincidences were generated. The energy calibration was performed using the energies of well-known lines in ^{48}Ti and other isotopes in the in-beam data.

The excitation functions were obtained by applying 15-*ns*-wide TOF gates on the γ-ray events in the interval E_n = 1 to 250 MeV. For each energy bin, a 1D γ-ray pulse-height spectrum was generated and fitted with computer code XGAM [5]. Detector efficiencies are calculated using MCNP calculation [6, 7] and checked with separate experimental runs with the same setup and same target, sandwiched between iron foils. The 847 keV line from the 2^+ level to the ground state transitions in ^{56}Fe is well studied at E_n=14.5 MeV [8]. Partial γ-ray cross sections for transitions were obtained using the following formula,

$$\sigma_\gamma(E_n) = (1+\alpha_\gamma) \times \frac{\varepsilon_{fc}}{\varepsilon_{Ge}} \times \frac{LT_{fc}}{LT_{Ge}} \times \frac{1}{a_s}\frac{A_\gamma}{N_n} \qquad (1)$$

where α_γ is the internal-conversion coefficient, ε_{Ge} and ε_{fc} are the detection efficiency of germanium detectors and fission chamber, LT_{Ge} and LT_{fc} are the live times of the germanium detectors and fission chamber, a_γ is the areal density of the ^{48}Ti sample, A_γ is the γ-ray peak area, and N_n the number of neutrons counted in the fission chamber.

MODEL CALCULATIONS

Calculations of the γ-ray production cross sections were performed using the EMPIRE-II statistical model code. EMPIRE uses the optical model, and includes coupled channels, Multistep Direct (MSD), Multistep Compound (MSC), Monte-Carlo preequilibrium emission and Hauser-Feshbach model. The general method of calculation involves assuming that the reaction proceeds in a series of two-body breakup processes. At each stage in the reaction, γ-ray and particle emission can occur and are computed using the Hauser-Feshbach compound-nucleus theory which conserves angular momentum and parity. Prior to the composite system reaching an equilibrated state, preequilibrium emission decay probabilities are computed. Optical model calculations of the total, elastic, and reaction cross sections, and the transmission coefficients for the Hauser-Feshbach calculations, were obtained using the ECIS-95 code. Optical model potentials are taken from the Reference Input Parameter Library [9]. For neutrons and protons the Kooning and Delaroche potential [10] was used and for alphas the Arthur and Young potential [11] developed for analyzing alpha-particle reaction data for medium nuclides was employed. For the level densities,the BCS + Fermi gas with deformation dependent collective effects, adjusted to experimental *a* values and to discretelevels are chosen. Preequilibrium spectra are determined using MSD and MSC calculations. These are performed using default parameters given in the EMPIRE code. Improvements to the current calculations by suitable adjustments of the input parameters are in progress.

RESULTS

The measured and calculated excitation functions as a function of incident neutron energy for prompt transitions in ^{48,47}Ti, ^{48}Sc, and ^{45}Ca following n+^{48}Ti reactions are shown in Figs. 1-4.

Fig. 1 displays the partial γ-ray transition cross section between the first 2^+ level and the ground state in the (n,n$'\gamma$) reaction channel, as a function of neutron energies up to 250 MeV. The EMPIRE calculation underpredicts the experimental value.

Fig. 2 shows the partial γ-ray transition cross section between the first excited level ($\frac{7}{2}^-$) and the ground state in the (n,2nγ) reaction channel, as a function of neutron energies up to 200 MeV. The EMPIRE calculation overpredicts the experimental value up to E_n=40 MeV and underpredicts above this point.

Fig. 3, and Fig. 4 show the partial γ-ray transition cross section for charged-particle emission channels as a function of incident neutron energies. For the (n,pγ) reaction channel, neutron energies up to 70 MeV and for (n,$\alpha\gamma$) channel neutron energies up to 200 MeV are displayed. There is a clear distinction between α emission and the 2p2n process in Fig.4. The EMPIRE calculations underpredict the measured values for these reaction channels.

In general, calculations with the default parameters underpredict the preequilibrium reaction emission. The EMPIRE calculations with default parameters reproduce

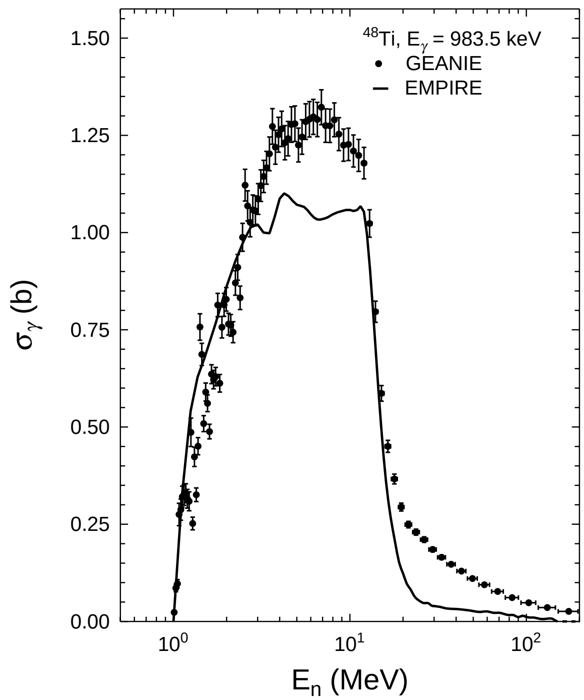

FIGURE 1. Partial γ-ray transition cross section for the E_γ=983.5 keV line in the ^{48}Ti(n,n$'\gamma$)^{48}Ti reaction, compared with calculation from EMPIRE code. Points with error bars: present experiment. Solid line: EMPIRE calculation with the default parameter set.

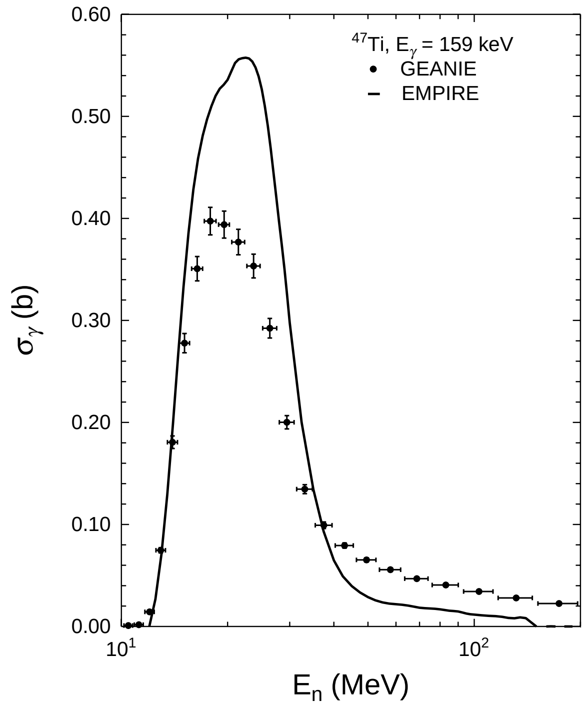

FIGURE 2. Partial γ-ray transition cross section for the E_γ=159 keV in the ^{48}Ti(n,2nγ)^{47}Ti reaction, compared with calculation from EMPIRE code. Points with error bars: present experiment. Solid line: EMPIRE calculation with the default parameter set.

reasonably well the shapes in the excitation functions of the reaction γ rays observed.

SUMMARY

An experiment was performed at the LANSCE/WNR spallation neutron source using the GEANIE γ-ray spectrometer and a scattering sample of ^{48}Ti. Excitation functions were extracted for ^{48,47}Ti, ^{48}Sc, and ^{45}Ca isotopes for transitions between the lowest excited level and ground state for neutron energies up to 250 MeV. The measurements are compared with the results of EMPIRE calculations for the partial γ-ray cross sections. The EMPIRE calculations use a Hauser-Feshbach model and account for preequilibrium reaction processes. The EMPIRE calculations reproduce reasonably well the shapes in the excitation functions of the reaction γ-rays observed. For all excitation functions, calculations underpredict the measured values in the energy region, where the preequilibrium reaction becomes more important.

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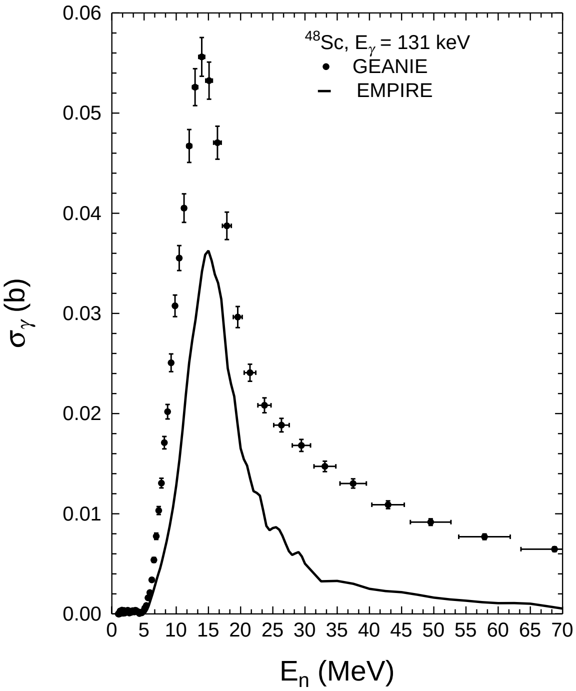

FIGURE 3. Partial γ-ray transition cross section for the E_γ=131 keV in the ^{48}Ti(n,pγ)^{48}Sc reaction, compared with calculation from EMPIRE code. Notation is the same as Fig. 1.

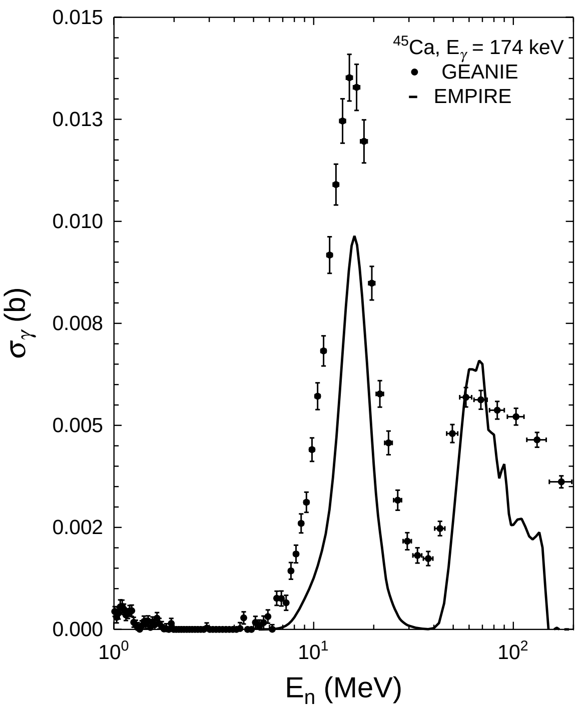

FIGURE 4. Partial γ-ray transition cross section for the E_γ=174 keV in the ^{48}Ti(n,$\alpha\gamma$)^{45}Ca reaction, compared with calculation from EMPIRE code. Notation is the same as Fig. 1.

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